Accelerator Physics -- Tevatron Task Force

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Temple Review

July 1, 2003

Overview

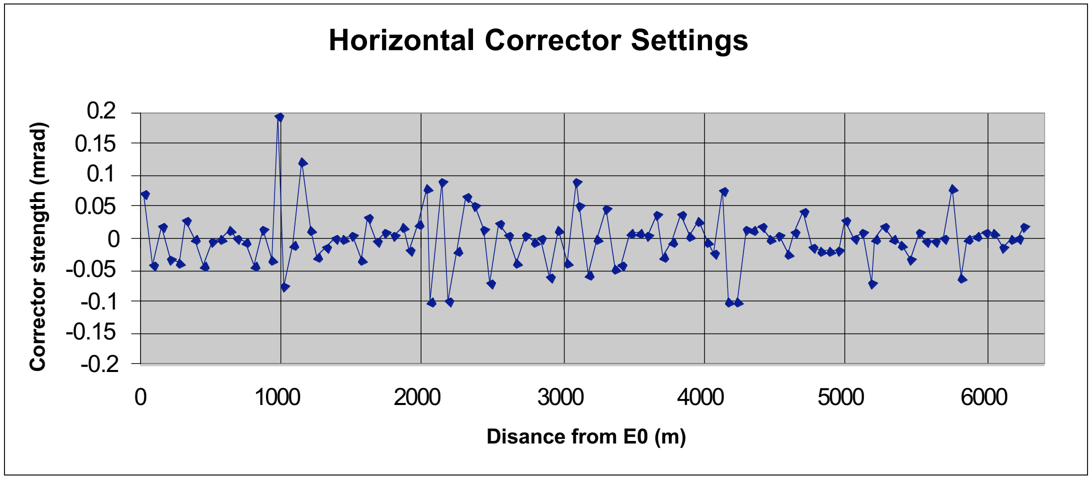
- Tevatron Accelerator Physics issues associated with Upgrade plan
  - Present understanding of Tevatron
  - Model(s) to assist in future projections
- Outline of talk:
  - Optics modeling
  - Luminosity modeling
  - Beam-beam interactions
    - Studies and simulations of long-range, head-on effects
    - Helical orbits
  - Beam halo, beam abort -- protection for detectors
  - Beam-beam compensation with wires
- Tevatron Task Force:
  - "Report on Tevatron Modeling and Accelerator Physics," see web site: http://www-bd.fnal.gov/doereview03/

Optics modeling

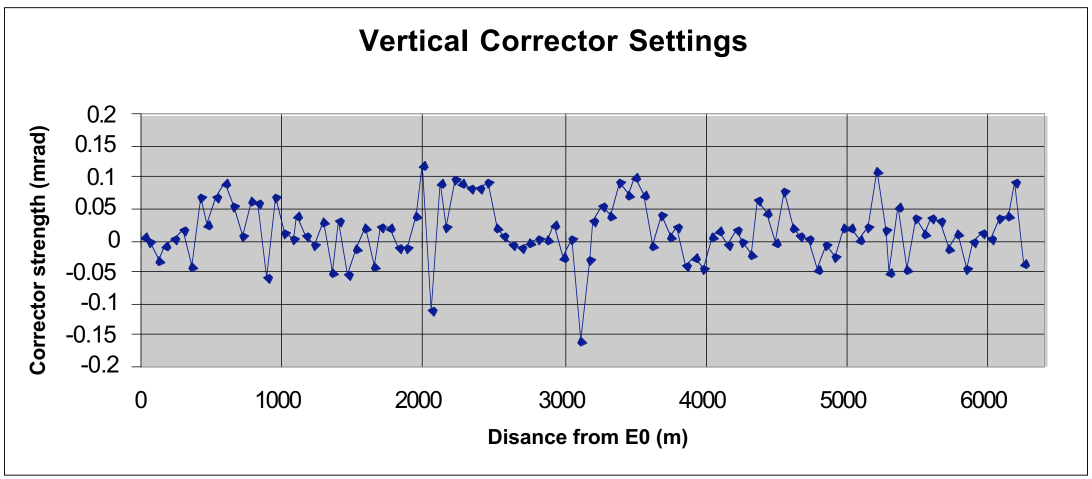
- Before attempting to interpret detailed models including beam-beam, resonance phenomena, etc., needed an improved understanding of basic lattice and low-order effects
  - o Immediate Goal: understand setting of each corrector/circuit
- Two major issues required resolution in order to better understand Tevatron operation:
  - o Strong orbit corrector settings
    - Many strong dipole correctors throughout the ring
    - Vertical dipole correctors running systematically strong -- $\langle\theta\rangle$ = 50-80 μrad in some regions (~0.4 km)
  - o Strong transverse coupling corrector settings
    - Skew quadrupole (0^{th} harmonic) circuit running strong to minimize tune split -- $\Delta\nu_{min}$ = 0.2-0.3 if left uncorrected; around long time, not understood
    - Separate skew quadrupoles in long-straight sections (esp. A0) required for global decoupling; strong correction

Orbit Corrections

- At 1 TeV, max dipole corrector strength = 0.13 mrad (50 A)



Corrector strengths used at 150 GeV to smooth the orbit. At 980 GeV, orbit distortion results as correctors run out of steam.

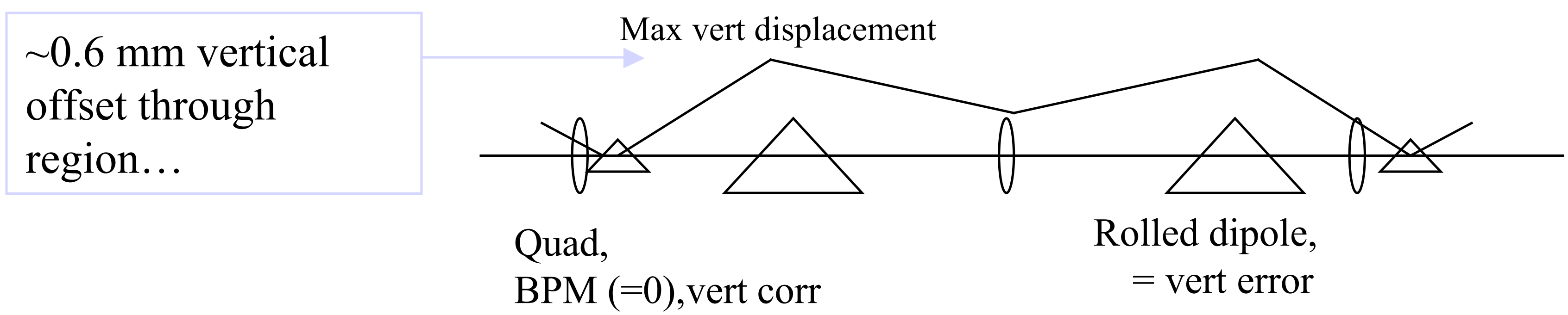


Note systematic offset of vertical correctors in several regions

Systematic Vertical Corrections in Tevatron

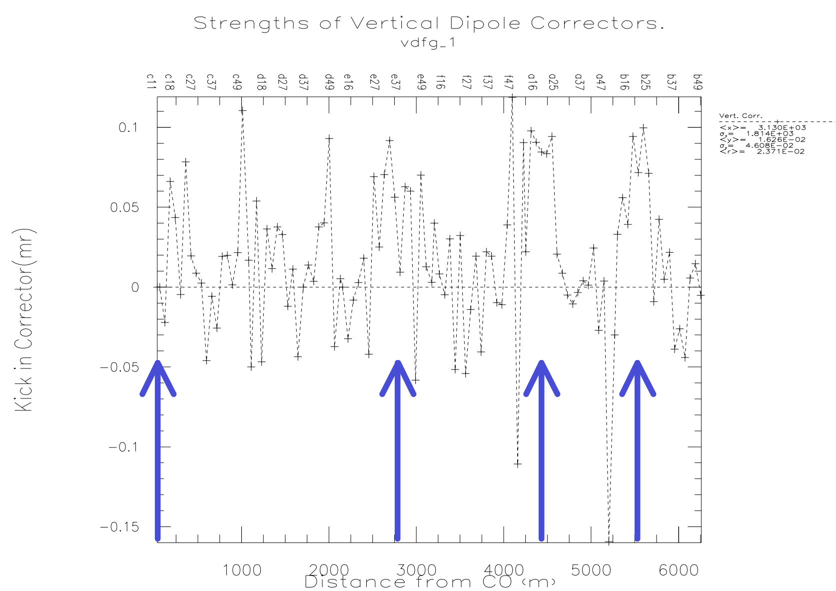
- Local systematic offsets in vertical corrector settings due to regions of tunnel with rolled dipole magnets
- Roll measurements in January confirmed understanding
- Major rolls being taken care of as time allows

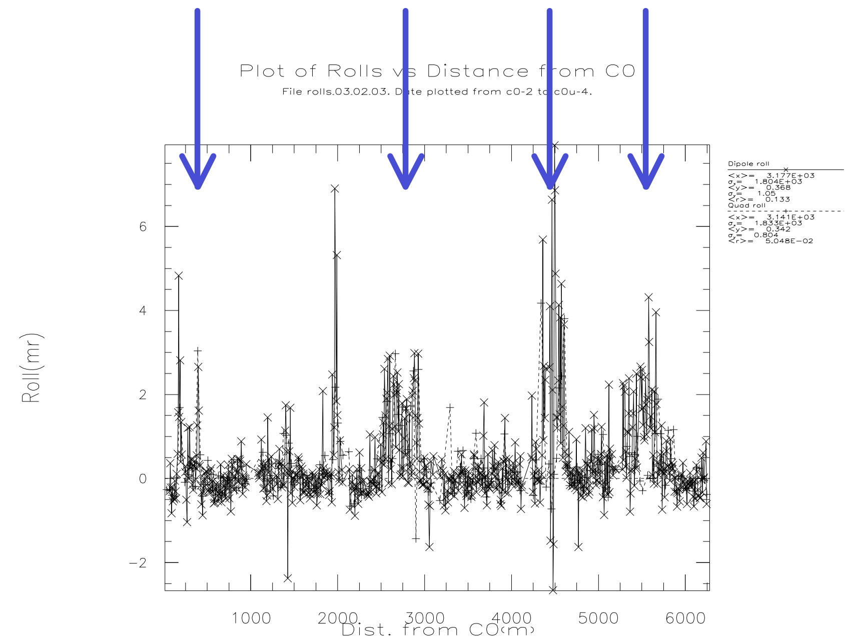
- Although BPM's read "zero", regions of "unseen" vertical distortions exist:



January Roll Measurements (R. Stefanski, et al.)

A "tilt-meter,, was used to measure roll angle of virtually every Tevatron magnet. Roll angles correlate very well with Vertical corrector settings

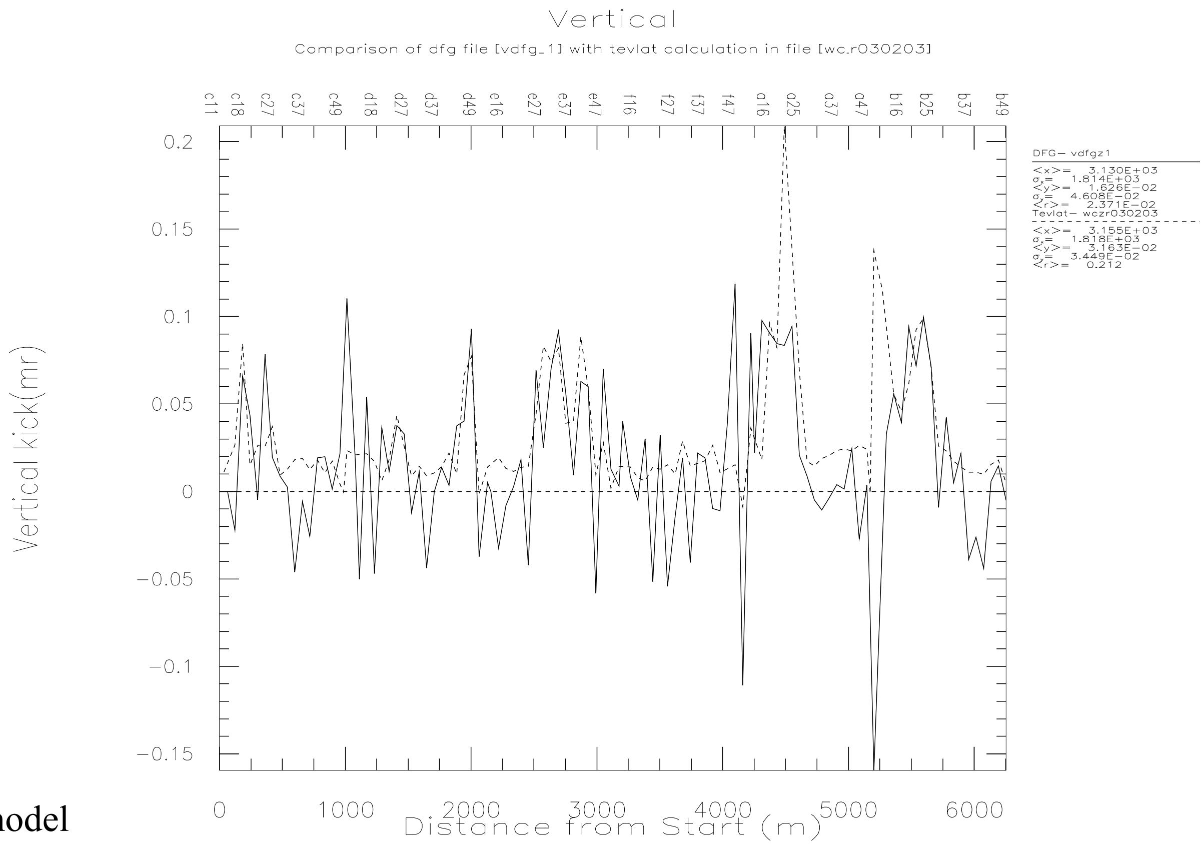




Corrector Settings (V) **Measured Roll Angles**

TEVLAT modeling (N. Gelfand)

- Magnet Database input (multipole data)
- Survey information
- Corrector settings (via control system)



Dash: model
Solid: control system

Corrector settings derived from model (with known roll and displacement misalignments as measured in tunnel) agree with actual settings

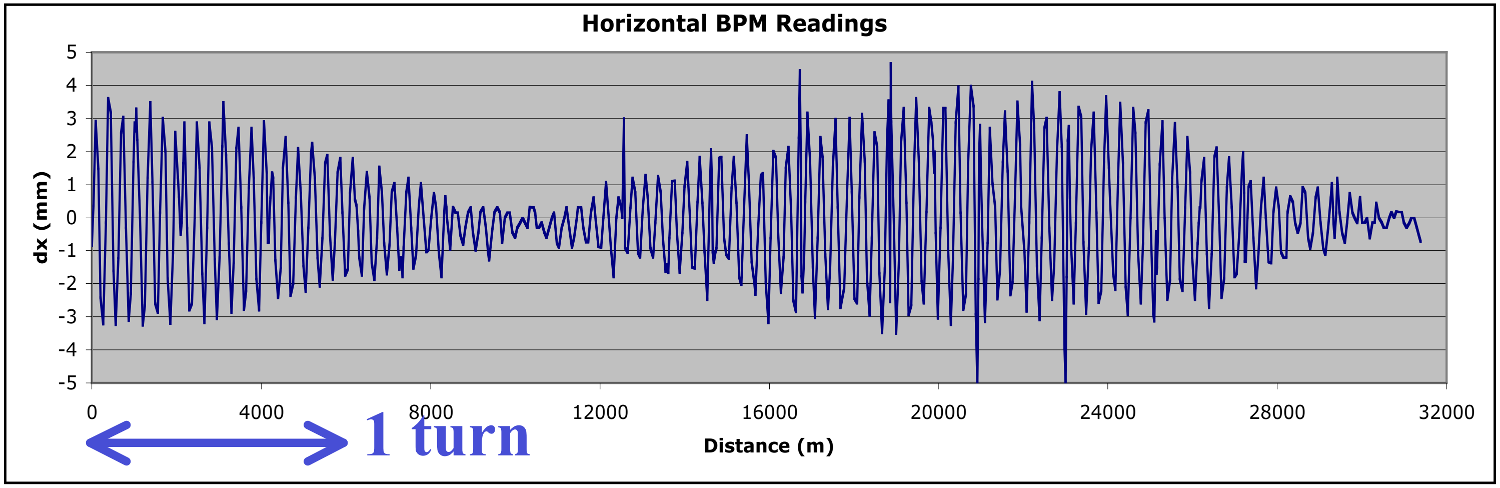
Transverse alignment not known as well, as data have been taken over long periods of time.

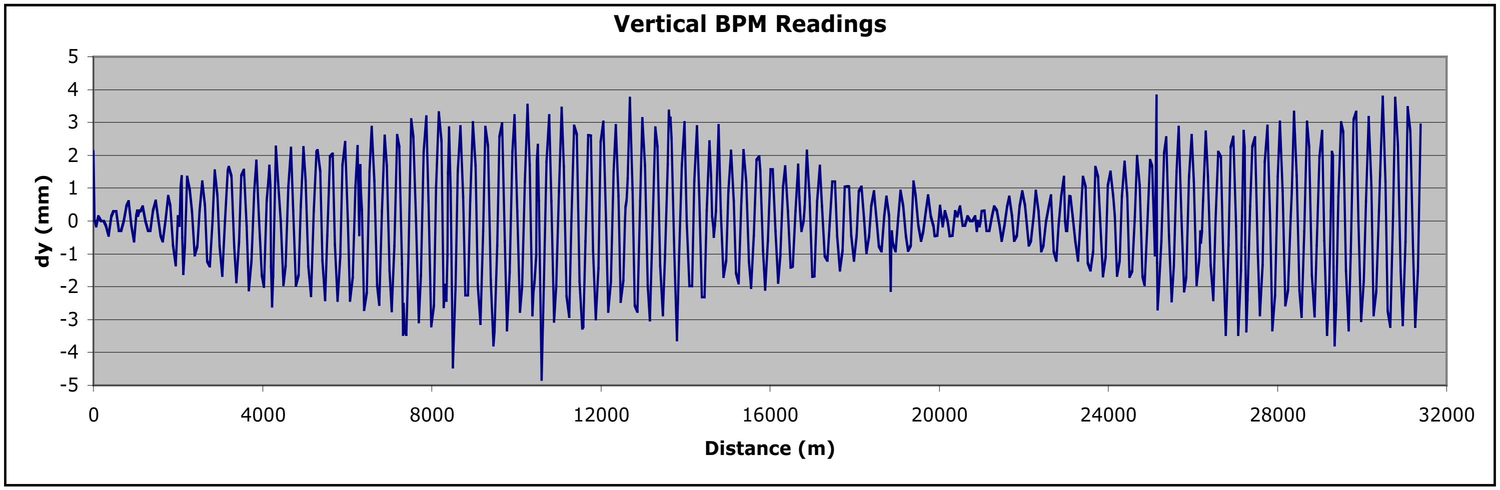
Strong Coupling in the Tevatron

- Systematic vertical displacements in dipole magnets produce transverse coupling due to feed-down; rolled quadrupole magnets produce coupling as well. Taken together, correction of these effects would be 10 times less than the skew quadrupole correction actually applied in the Tevatron.
- In February 2003, experiments showed that coupling is *distributed uniformly* around the ring
  - Suggest skew quad $a_1 = 10^{-4}$/in within each dipole
  - Similar value agrees with skew quad setting:

$$\Delta\nu_{min} = 2Fa_1 = 2{*}25\text{m}{*}(10^{-4}/25\text{mm}) = 0.2$$

Coupling Data, Feburary 27, 2003





Data are consistent with systematic $a_1 \sim 1.4\text{x}10^{-4}$/in

G. Annala

a_1 in the Tevatron Dipoles

- Simultaneously (almost to the day), Technical Division analyzed measurements made of "Smart Bolts" on ~20 Tevatron dipole magnets in the tunnel. Found that the coil had shifted (downward) by about 0.004 inch within the iron yoke of each magnet. This leads to a skew quadrupole component:

$$a_1 = 2\frac{(c/R)^2}{1+(c/R)^2}\frac{\Delta}{R^2} = 2\frac{0.25}{1.25}\frac{0.004}{(3.8)^2\text{in}} = 1.1\times 10^{-4}\,/\text{in}$$

c/R = ratio of coil radius to yoke radius

- Since then, more than 80 magnets have been measured, confirming a systematic skew quadrupole moment has developed

Optics -- conclusions

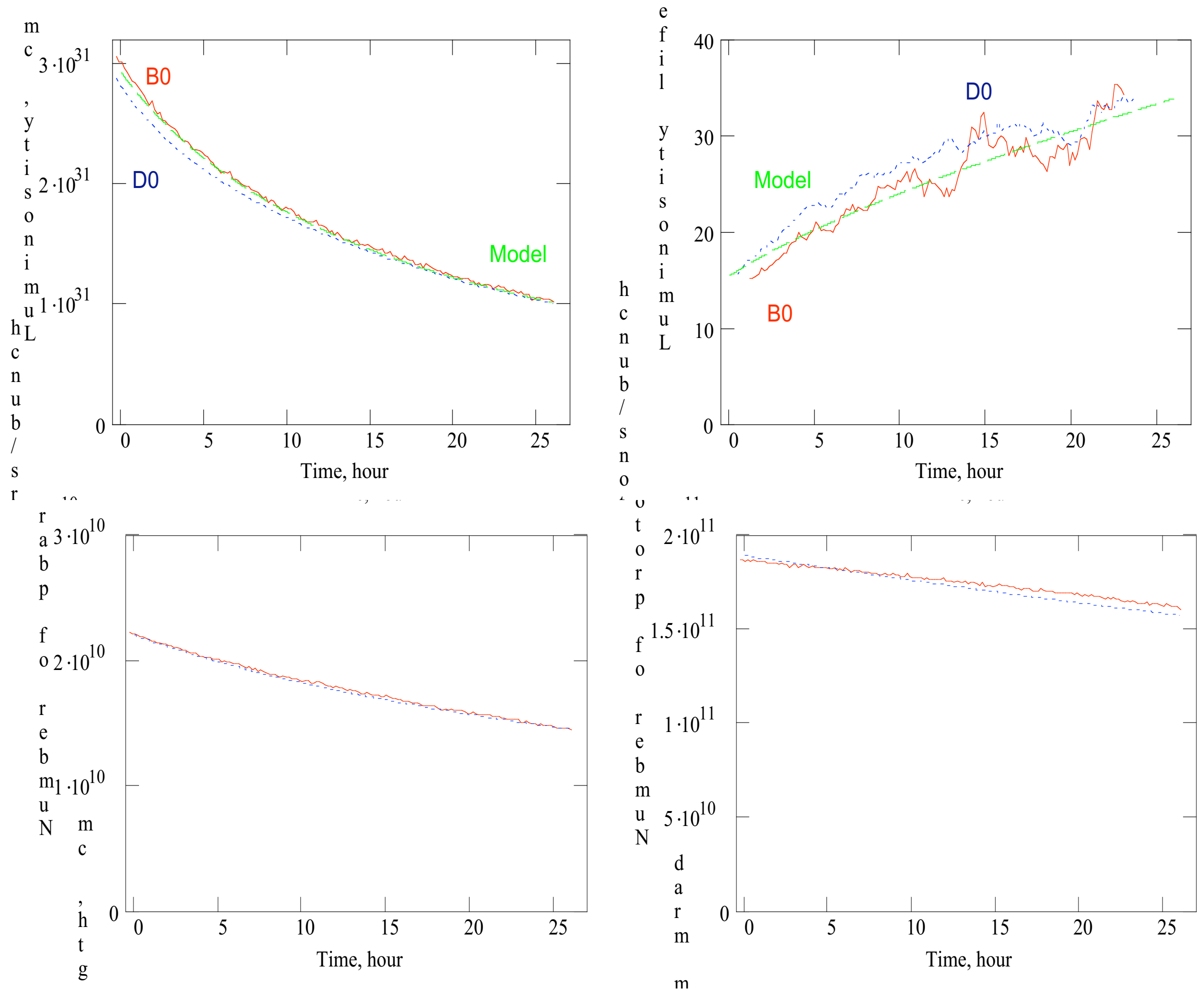
- Understanding of Tevatron optics has improved immensely over past 8 months.
  - Settings of correctors are well understood, and major source of transverse coupling has been identified
  - Coupling sources and their correction leads to vertical dispersion (~0.5-0.8 m) in Tevatron, which is verified by measurements and models
  - Models have been generated using several codes -- TEVLAT (Gelfand), MAD (Xiao), OptiM (Lebedev), for example -- and all agree with measurements and with each other to good degree.
  - More precise understanding can be obtained with upgrade to BPM system -- resolution, memory (turn-by-turn), and reliability.
    - Necessary for next steps: nonlinear dynamics effects

Luminosity Lifetime Model

The model takes into account the major beam heating and particle loss mechanisms

- **Phenomena taken into account**
  - Interaction with residual gas
    - Emittance growth due to electromagnetic scattering
    - Particle loss due to nuclear and electromagnetic interaction
  - Particle interaction in IPs (proportional to the luminosity)
    - Emittance growth due to electromagnetic scattering
    - Particle loss due to nuclear and electromagnetic interaction
  - IBS
    - Energy spread growth and emittance growth due to multiple scattering
  - Bunch lengthening due to RF noise
  - Particle loss from the bucket due to heating of longitudinal degree of freedom
- **Phenomena ignored in the model**
  - Beam-beam effects
  - Non-linearity of the lattice
  - Diffusion amplification by coherent effects
- Thus, it can be considered as **the best-case scenario**
  - It describes well our present best stores

Comparison of the Model Predictions to the Store 2138 (Jan 5 2003)



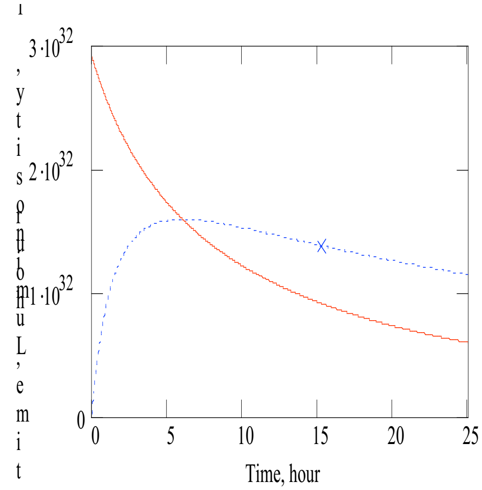
Model overestimates the bucket losses at the store beginning ==> too fast decay of the proton intensity in the model

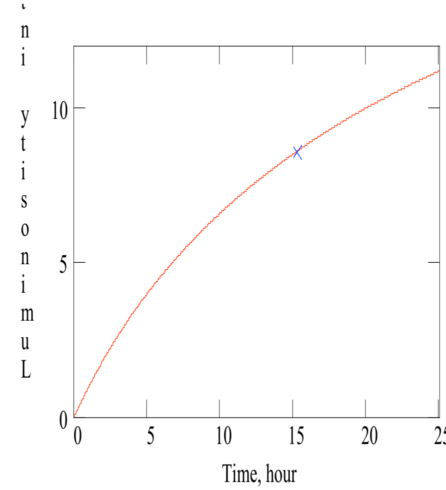
Basic Luminosity Scenario

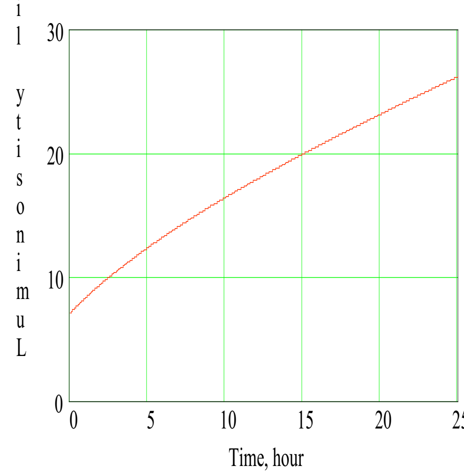
Luminosity integral is calculated presuming:

- Machine runs 46 weeks per year (6 weeks of shutdown time)
- There are 48 hours of downtime per week
- Shot setup time is 2 hours. (Not included in the downtime.)

Balanced approach for both Tevatron and Antiproton source parameters







$N_p = 2.7 \times 10^{11}$

$N_a = 1.351 \times 10^{11}$

$\varepsilon n_{px} \cdot 10000 = 20$ mm mrad

$\varepsilon n_{py} \cdot 10000 = 20$ mm mrad

$\varepsilon n_{ax} \cdot 10000 = 20.07$ mm mrad

$\varepsilon n_{ay} \cdot 10000 = 20.07$ mm mrad

$\sigma s(\sigma_{pp}) = 50.143$ cm

$\sigma s(\sigma_{pa}) = 50.143$ cm

$T_{store} = 15.2$ hour

$\kappa = 0.2$

$dNadt \cdot 10^{-10} = 40$ mA/Hour

$N_{recycle} \cdot 10^{-10} = 0$ mA

$N_a \cdot n_b \cdot 10^{-10} = 486.4$ mA

$Lum_0 = 2.907 \times 10^{32}$ cm^{-2}s^{-1}

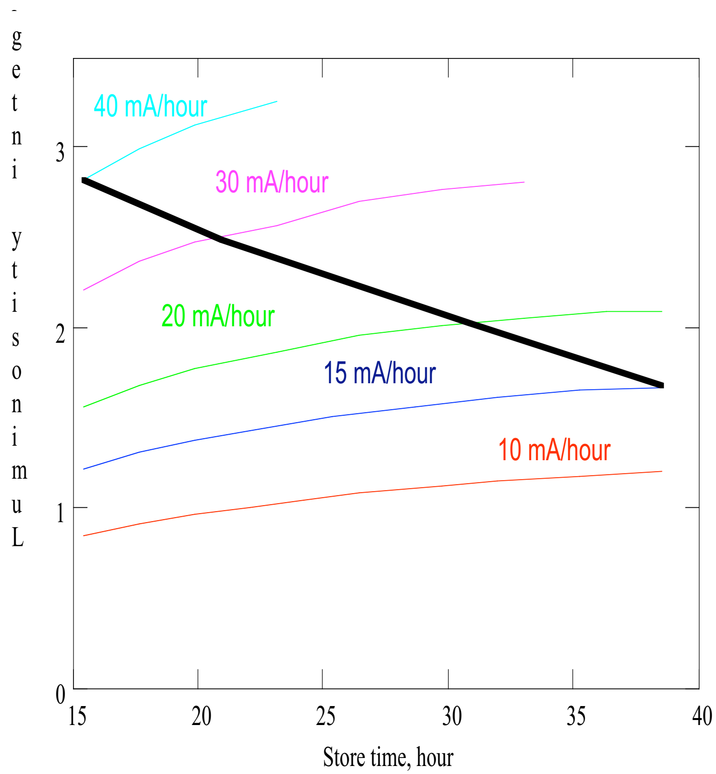
$Lum_{avrg} = 1.385 \times 10^{32}$ cm^{-2}s^{-1}

$\tau_{Lum_1} = 7.037$ hour

$Ldt_{year} = 2.751$ fbarn/year

$SLum_{T_{store} \cdot 60} = 8.568$

Optimal Store Times



Dependencies of luminosity integral per year on the store time for different antiproton production rates. Thick solid line shows where intensity of antiproton beam reaches $1.35 \cdot 10^{11}$ per bunch.

Lifetime breakdown at beginning of store

	hours
Luminosity	7.0
Prot.intens	.51
Pbar.intens	.29
Prot.H.emit	.9
Prot.V.emit	.30
Pbar.H.emit	.16
Pbar.V.emit	.48
Hourglass factor	32

$$L = \frac{N_p N_{\bar{p}} f_0 n_b}{2\pi\beta^* \sqrt{\left(\varepsilon_{xp} + \varepsilon_{x\bar{p}}\right)\left(\varepsilon_{yp} + \varepsilon_{y\bar{p}}\right)}} H\left(\frac{\sqrt{\sigma_{sp}{}^2 + \sigma_{s\bar{p}}{}^2}}{\beta^*}\right)$$

Present and final Run II parameters of the collider

	Store 2328	Typical for April 2003	Final Run II
Number of protons per bunch, 10^{10}	20.7	20	27
Number of antiprotons per bunch, 10^{10}	2.54	2.2	13.5
Normalized 95% proton emittances, $\varepsilon_x / \varepsilon_y$, mm mrad	~14/24	~15/25	20/20
Normalized 95% antiproton emittances, $\varepsilon_x / \varepsilon_y$, mm mrad	~15/24	~16/25	20/20
Proton bunch length, cm	65	62	50
Antiproton bunch length, cm	59	58	50
Initial luminosity, 10^{30} cm^{-2}s^{-1}	40.5	35	290
Initial luminosity lifetime, hour	11	12	7.1
Store duration, hour	19	20	15.2
Luminosity integral per store, pbarn	1.71	1.2	8.65
Shot setup time, hour	2	2	2
Number of store hours per year	-	-	4800
Luminosity integral per year, fbarn	-	-	2.78
Transfer efficiency from stack to Tevatron at low-beta	60%	59%	80%
Average antiproton production rate, 10^{10}/hour	-	11	40
Total antiproton stack size, 10^{10}	166	150	610
Antiprotons extracted from the stack, 10^{10}	154	140	610

Beam-Beam interactions

- Beam-beam effects are important at all stages
  - Injection
  - Acceleration
  - Squeeze
  - Collision
- Two types of beam-beam effects
  - **Head-on**
    - Run IB proton bunch population of ~$2.7 \cdot 10^{11}$ proton/bunch was set by the head-on collisions
    - We aim to achieve the same number of protons per bunch
    - Linear beam-beam tune shift $\xi \approx 0.02$ for two interaction points
  - **Long range**
    - Much stronger than for Run IB
    - Additional tune spread within one bunch

      $\Delta\nu \approx 5 \cdot 10^{-3}$
    - Tune spread between bunches ($N_p = 2.7 \cdot 10^{11}$)

      At injection: $\Delta\nu_x \approx 5 \cdot 10^{-3}$, $\Delta\nu_y \approx 2.5 \cdot 10^{-3}$

      At flat top: $\Delta\nu_x \approx \Delta\nu_y \approx 8 \cdot 10^{-3}$

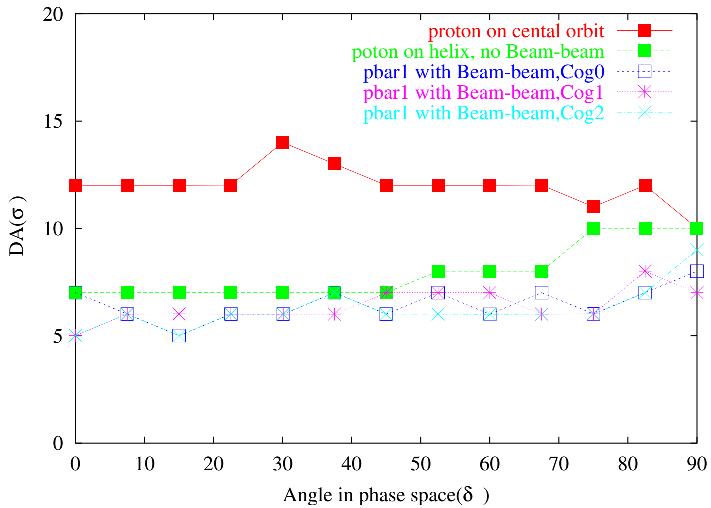
Injection Dynamic Aperture Calculations

Note:

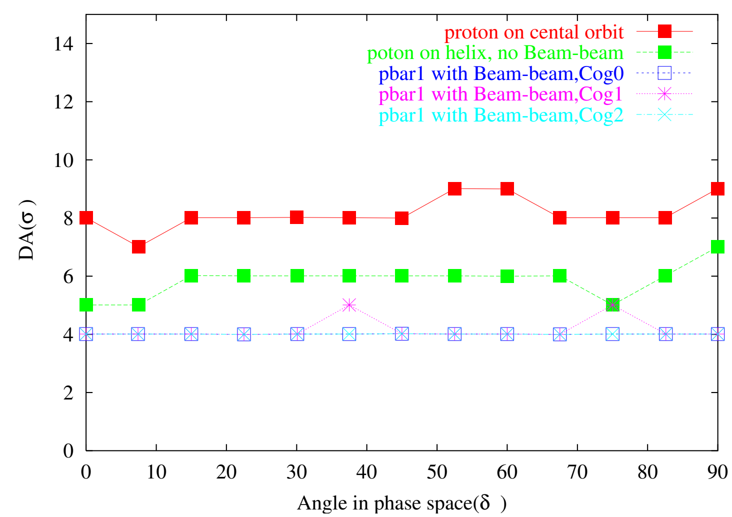
$(\varepsilon\beta/6\pi\gamma)^{1/2}$ ~ 1.5 mm

$D\,\sigma_p/p$ ~ ***3 mm***

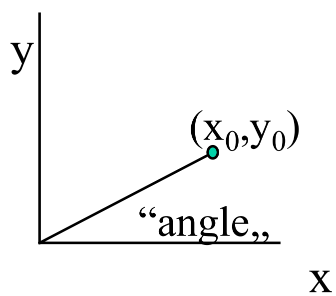
Pre/Early-Run studies
15π emittance, dp/p=1e-4 (1σ),
$\nu_{x,y}$=(0.585,0.575), Original helix



Present Conditions
25π emittance, dp/p=13e-4 (3σ),
$\nu_{x,y}$=(0.583,0.575), "new-new" helix



(M. Xiao)



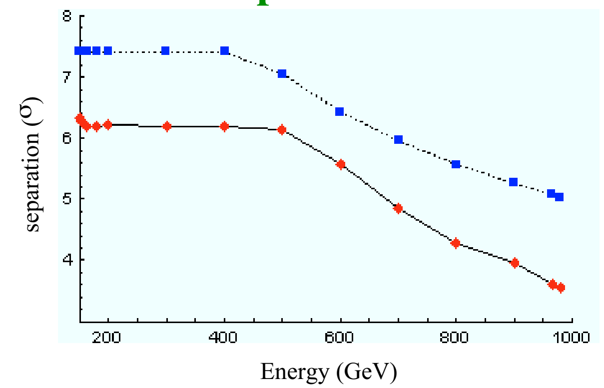
Starting at B0, center of beam - beam kick; 10^5 turns

Behavior on/off helix consistent with DA calculations

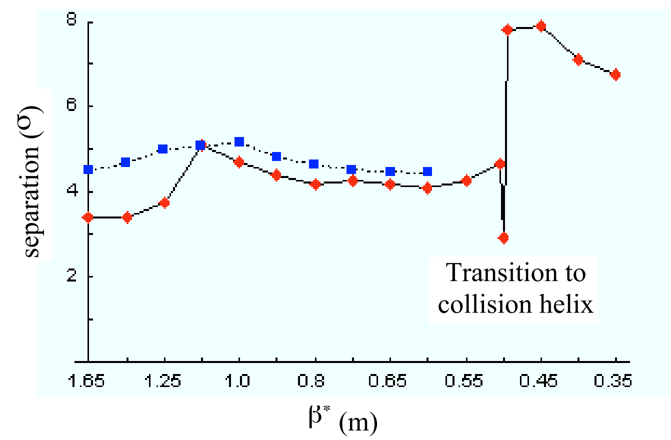
Beam separation and long range beam-beam

- For fixed separation in σ's, tune shift does not depend on energy
- Separation requires
  voltage ∝ √Energy
- High voltage separators are maxed-out at ~ 500 GeV
- This reduces the beam separation at the end of acceleration by factor of 1.4 times
- Acceleration and squeeze are the most sensitive steps from the beam-beam effects point of view
- Normally particles which survive acceleration and squeeze do not experience severe beam-beam effects during the store

Injection Helix after C0 Lambertson Replacement



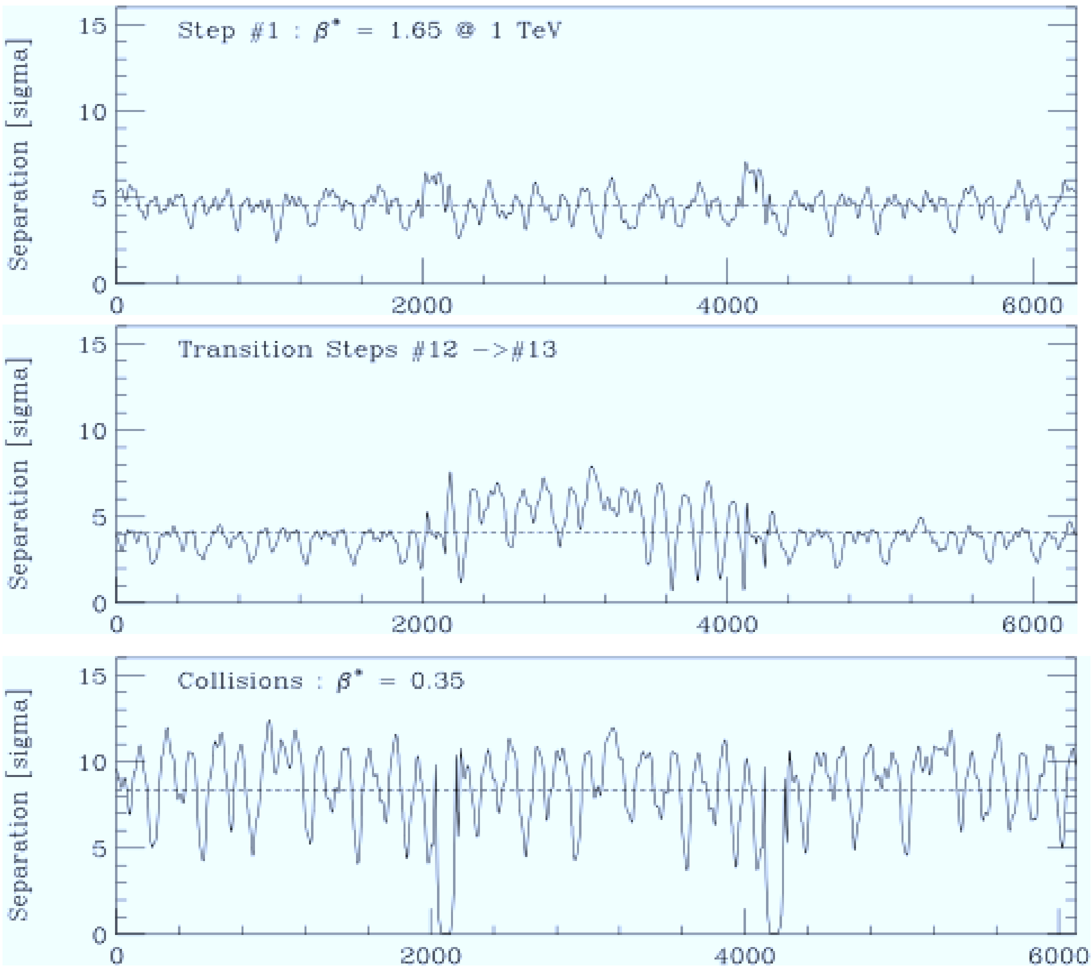
Separation up the ramp (current and new settings)



Separation on squeeze (Umax=106.5 kV, E=1 TeV)

Helical Orbits

Present helix manipulation during low-beta squeeze generates small beam separation in the arcs of the collider

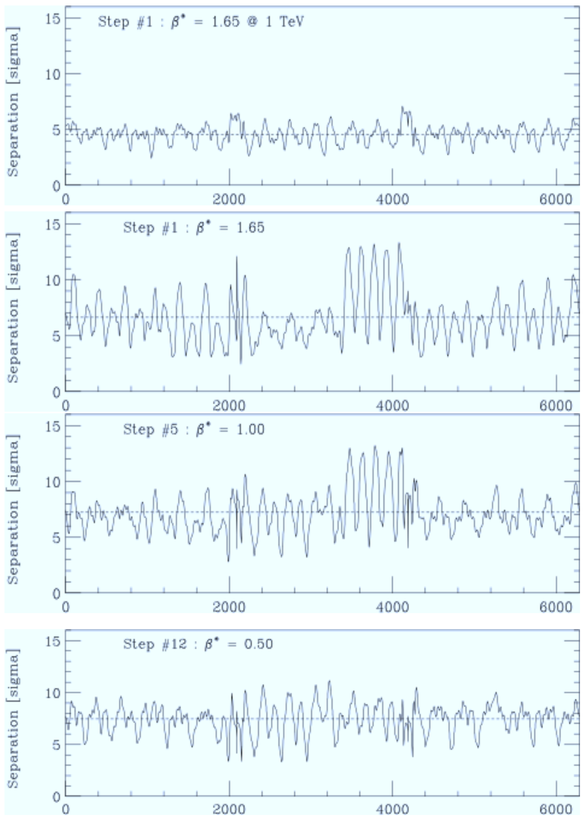


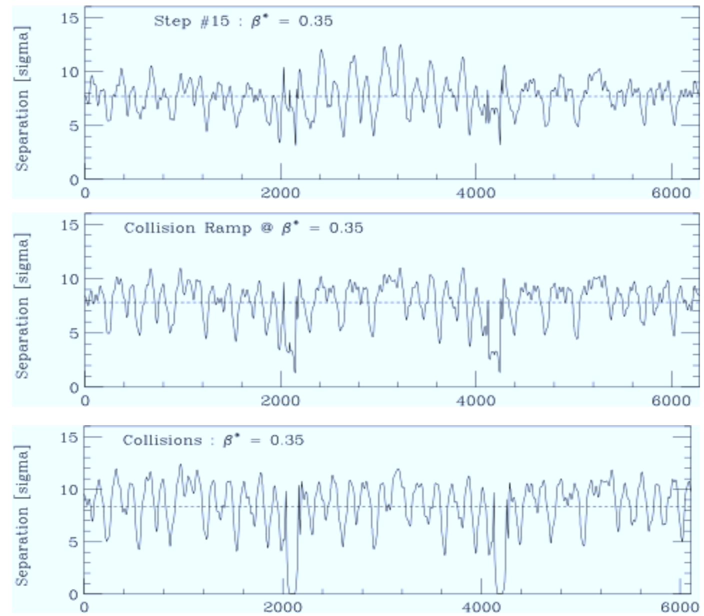
- Two separators are used from injection to "step 1" and then more (12 total) are phased in

- The result is a small separation part-way through the sequence.

Helical Orbits

Use other separators to convert the injection helix to one more appropriate for the changing optics, and better control the orbits during the squeeze…



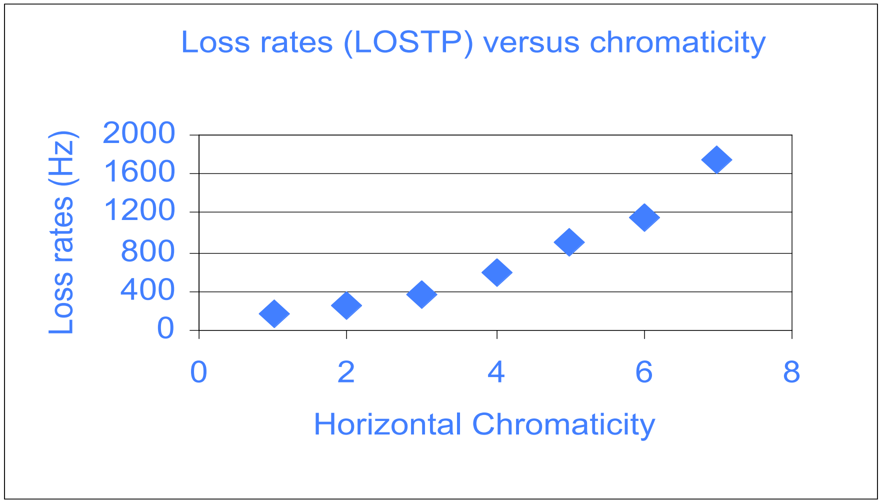


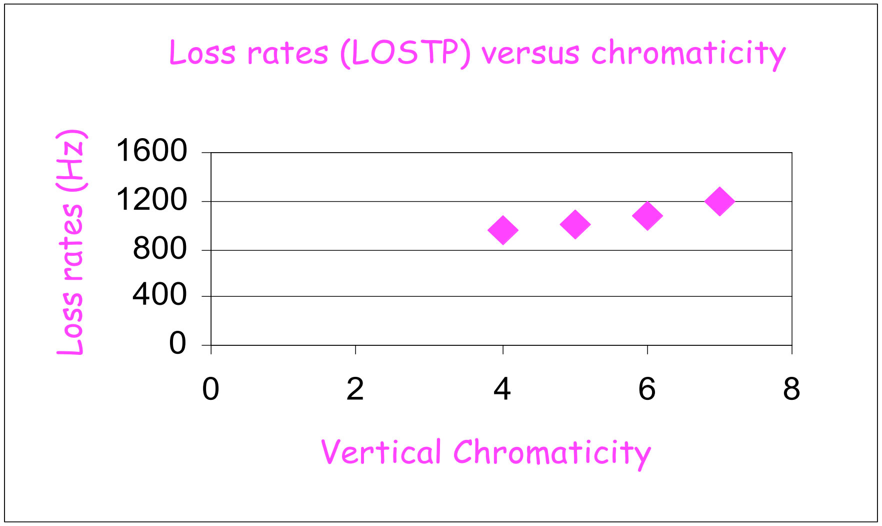
Here, use existing elements; requires refinement of tunes, coupling feed-down circuits, etc. -- study time!
-- not yet implemented

Possible hardware improvements to address long-range collisions

- Adding new separators to correct the betatron phase imbalances along the machine
  - Optics change in A0 could additionally improve separation but presently is not favorable due to comparatively large cost involved
- Increasing deflections of the near IP separators by 1.4 times
  - Increasing voltage
  - Dielectric or semiconducting covering of the plates?
  - Training to higher voltage
- Increasing length of separators
  - We can use the space where non-powered Q1 quads are presently located
- Tevatron electron lens can reduce both long range and head-on tune shifts
  - Recently we achieved electron lens operation without degradation of the beam lifetime

Lower chromaticity mitigates effects of non-linearities and beam-beam





♦Lower chromaticity is better for lifetime

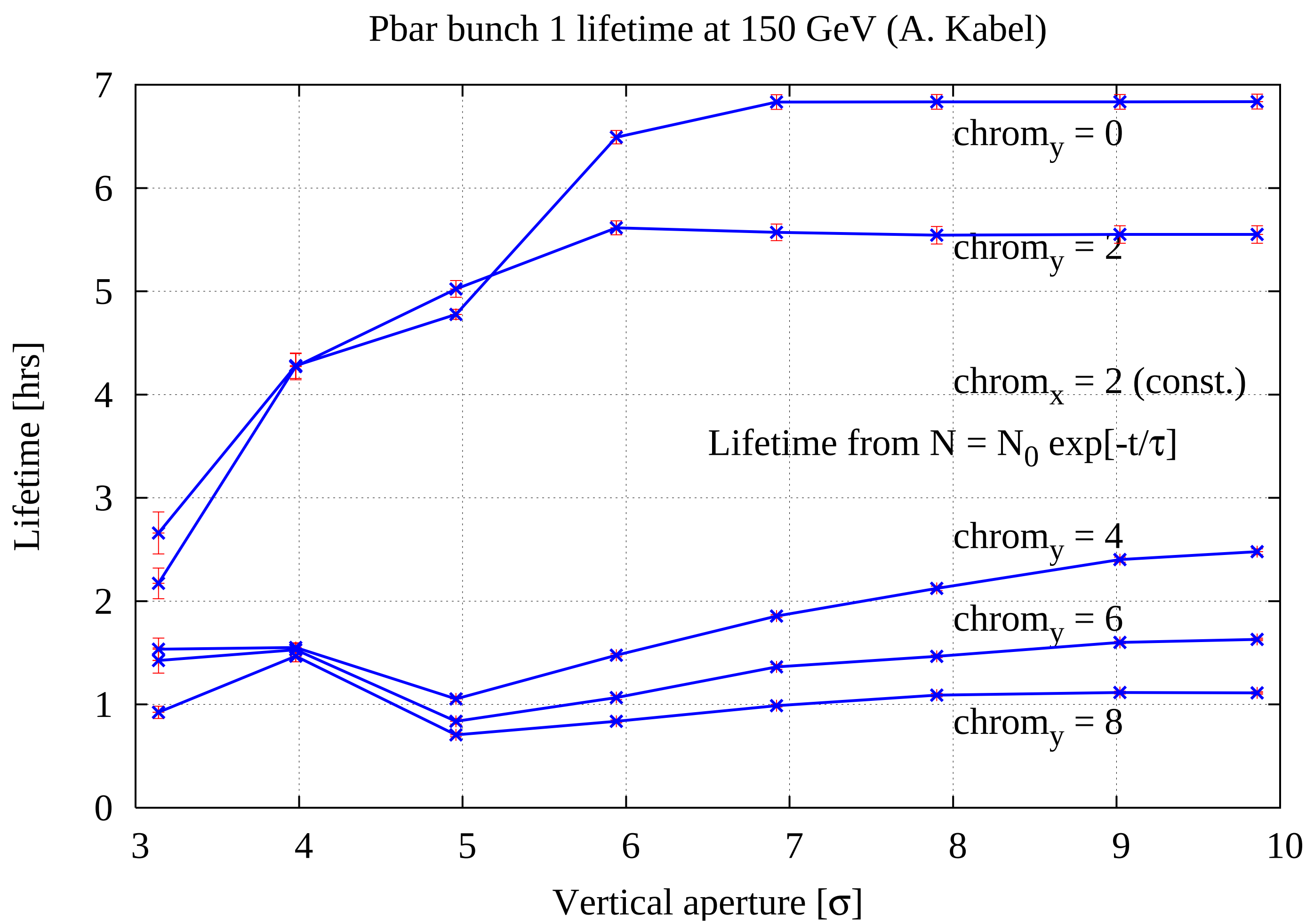
♦Instabilities appear ξ < 3-4

♦Run with $\xi_H = 8$, ξ_V=8 to avoid instabilities

♦Dampers allow us to lower chromaticity and improve lifetime

Measured loss rates as function of chromaticity (with protons on the pbar helix)

Multiparticle Simulations



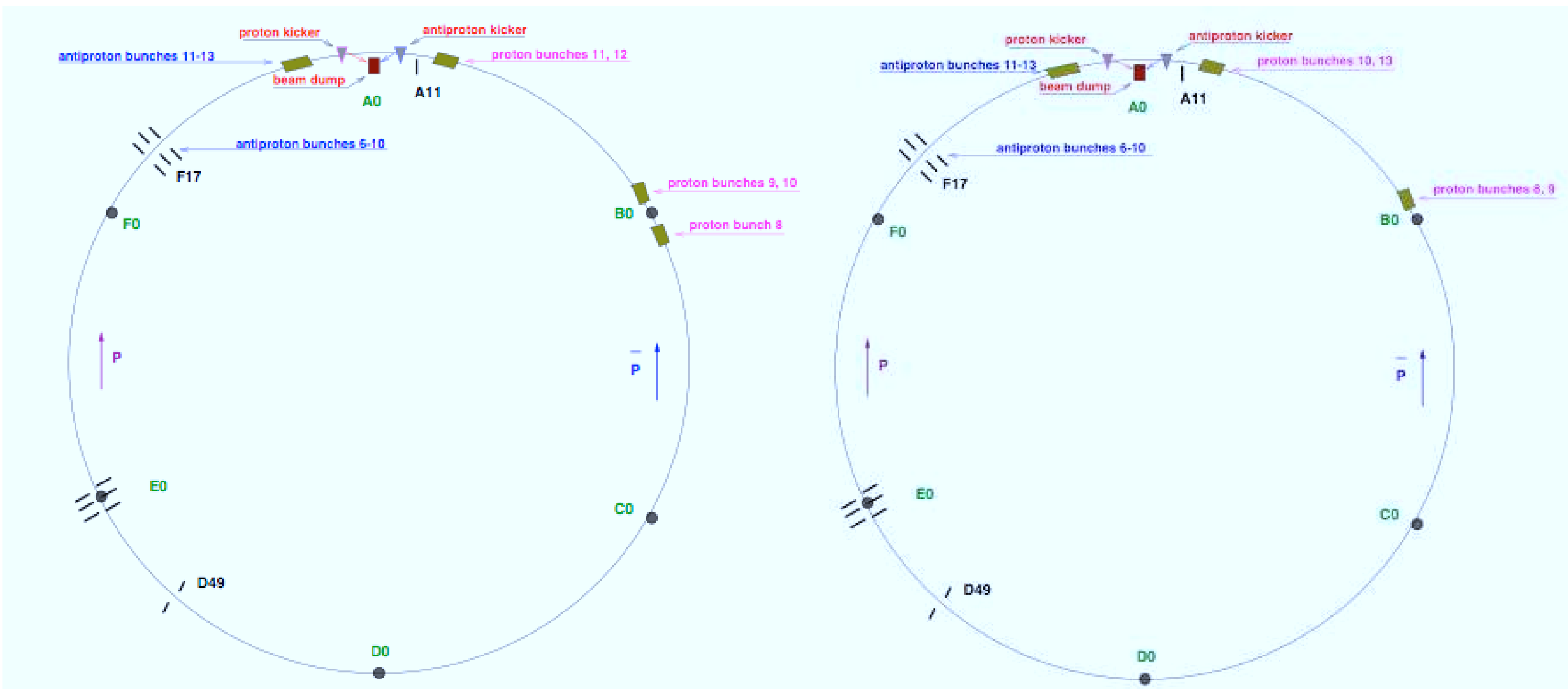
Lifetime of antiproton Bunch 1 vs physical aperture for various vertical chromaticities (simulation by A. Kabel (SLAC)). Proton intensity per bunch $2.2 \cdot 10^{11}$, horizontal chromaticity fixed at 2 units.

Beam halo, beam abort -- detector protection

- Simulations of particle loss and energy deposition performed of CDF/B0 region:
  - o Goal: Reduce background in main CDF detector
  - o Goal: Protect CDF detector from abort kicker pre-fire
  - o Result: single L-shaped collimator at A48 location --
    - protects low-β quads and CDF silicon detectors from abort kicker pre-fire
    - Reduces backgrounds at CDF detector by 2-3 times
  - o Proposal reviewed in June 03, to be installed in late summer 03

Abort kicker pre-fire protection

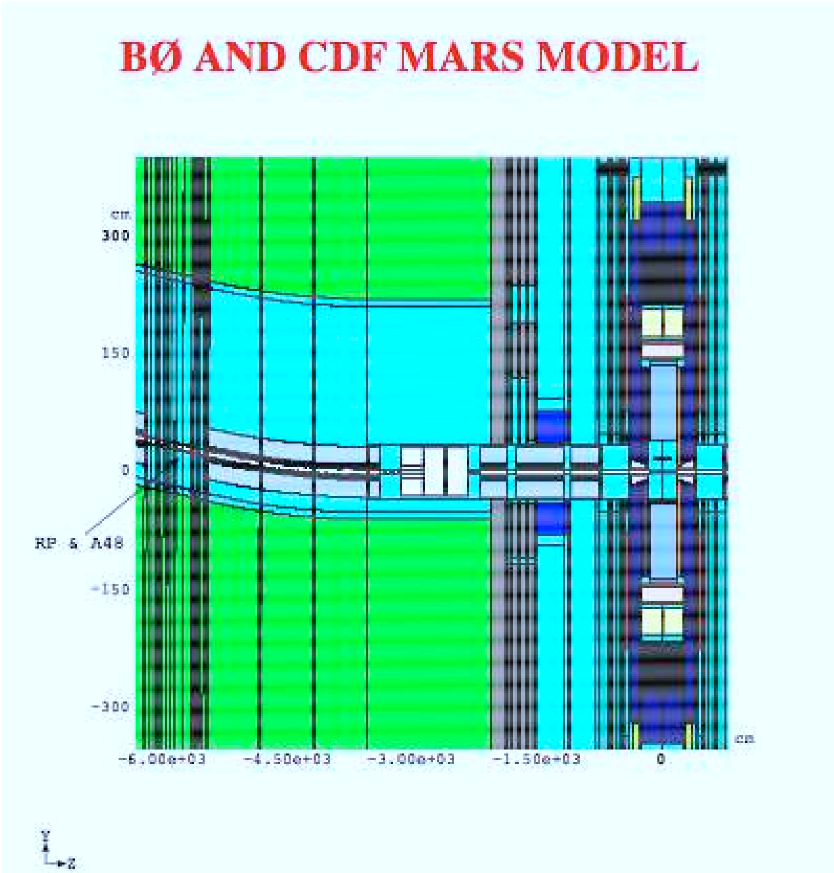
- Particle loss locations in the Tevatron due to
  - o Proton abort kicker pre-fire (left)
  - o Antiproton abort kicker pre-fire (right)

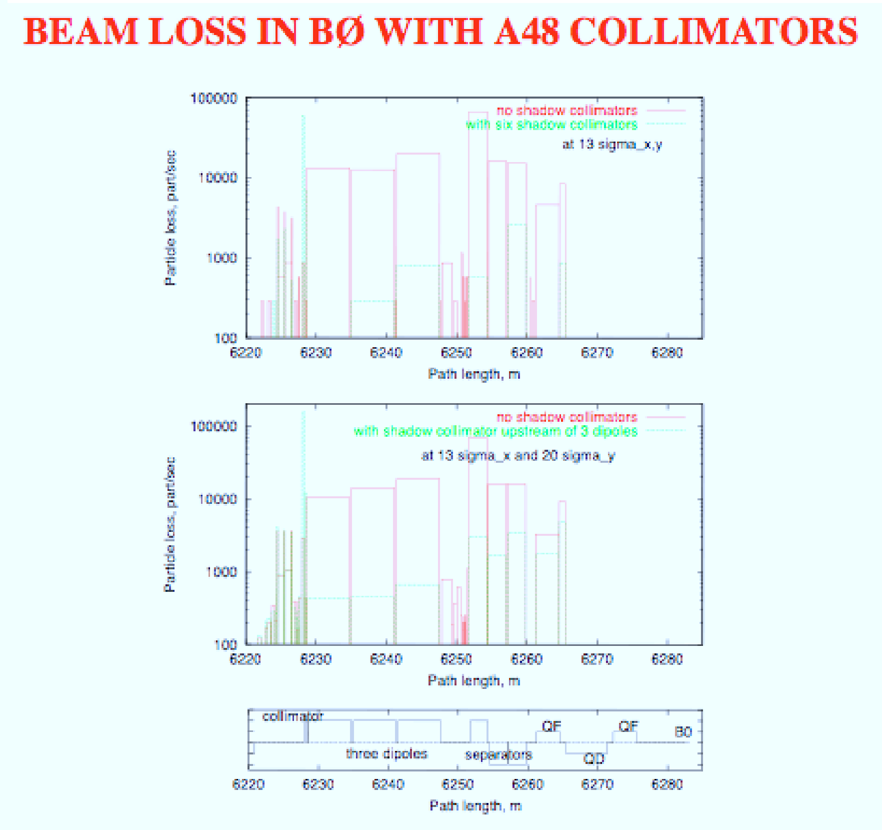


bunches not indicated are lost on the abort beam dump

Energy Deposition and detector background modeling

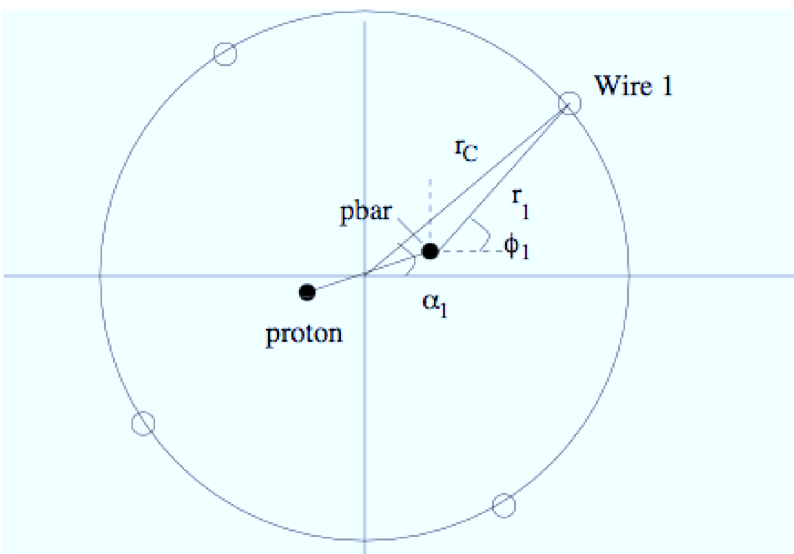
- Extensive modeling of CDF region to simulate present conditions, and compare with proposed A48 collimator (Mokhov, Drozhdin, Nicolas)





Beam-beam compensation with wires

- Beginning to study long-range beam-beam compensation using current-carrying wires…
  - o near to and running parallel to the antiproton beam
  - o Produces forces resembling long-range forces produced by passing proton bunches
  - o Proposed by CERN (Koutchouk) for use in LHC; on-going collaborative effort
- With a "cage" of wires, can produce arbitrary multipole coefficients



$$B_y + iB_x = \frac{\mu_0}{2\pi} I_W \sum_{j=1}^{N_W} \sum_{n=0}^{\infty} [-\cos(n+1)\phi_j + i\sin(n+1)\phi_j] \left[\frac{(x+iy)^n}{r_j^{(n+1)}} \right]$$

$$r_j = [(r_C \cos\alpha_j - r_{\bar{p}} \cos\theta_{\bar{p}})^2 + (r_C \sin\alpha_j - r_{\bar{p}} \sin\theta_{\bar{p}})^2]^{1/2}$$

$$\phi_j = \arctan\left[\frac{(r_C \sin\alpha_j - r_{\bar{p}} \sin\theta_{\bar{p}})}{(r_C \cos\alpha_j - r_{\bar{p}} \cos\theta_{\bar{p}})} \right]$$